



TechBriefs

National Aeronautics and
Space Administration



Electronic Components and Circuits



Electronic Systems



Physical Sciences



Materials



Computer Programs



Mechanics



Machinery



Fabrication Technology



Mathematics and Information Sciences



Life Sciences

INTRODUCTION

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NASA Field Centers and Program Offices

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Carolina Blake
(650) 604-1754 or
cblake@mail.arc.nasa.gov

Dryden Flight Research Center

Jenny Baer-Riedhart
(661) 276-3689 or
jenny.baer-riedhart@dfrc.nasa.gov

Goddard Space Flight Center

George Alcorn
(301) 286-5810 or
galcorn@gsc.nasa.gov

Jet Propulsion Laboratory

Merle McKenzie
(818) 354-2577 or
merle.mckenzie@jpl.nasa.gov

Johnson Space Center

Hank Davis
(281) 483-0474 or
henry.l.davis1@jsc.nasa.gov

John F. Kennedy Space Center

Jim Aliberti
(321) 867-6224 or
Jim.Aliberti-1@ksc.nasa.gov

Langley Research Center

Sam Morello
(757) 864-6005 or
s.a.morello@larc.nasa.gov

Glenn Research Center

Larry Viterna
(216) 433-3484 or
cto@grc.nasa.gov

George C. Marshall Space Flight Center

Vernotto C. McMillan
(256) 544-2615 or
vernotto.mcmillan@msfc.nasa.gov

John C. Stennis Space Center

Kirk Sharp
(228) 688-1929 or
technology@ssc.nasa.gov

NASA Program Offices

At NASA Headquarters there are seven major program offices that develop and oversee technology projects of potential interest to industry:

Carl Ray

Small Business Innovation
Research Program (SBIR) &
Small Business Technology
Transfer Program (STTR)
(202) 358-4652 or
cray@mail.hq.nasa.gov

Dr. Robert Norwood

Office of Commercial Technology
(Code RM)
(202) 358-2320 or
rnorwood@mail.hq.nasa.gov

John Mankins

Office of Space Flight (Code MP)
(202) 358-4659 or
jmankins@mail.hq.nasa.gov

Terry Hertz

Office of Aero-Space Technology
(Code RS)
(202) 358-4636 or
thertz@mail.hq.nasa.gov

Glen Mucklow

Office of Space Sciences
(Code SM)
(202) 358-2235 or
gmucklow@mail.hq.nasa.gov

Roger Crouch

Office of Microgravity Science
Applications (Code U)
(202) 358-0689 or
rcrouch@hq.nasa.gov

Granville Paules

Office of Mission to Planet Earth
(Code Y)
(202) 358-0706 or
gpaules@mtpe.hq.nasa.gov



National Aeronautics and
Space Administration

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Electronic Components and Circuits

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Microcavity Device for Measuring Direction of a Laser Beacon

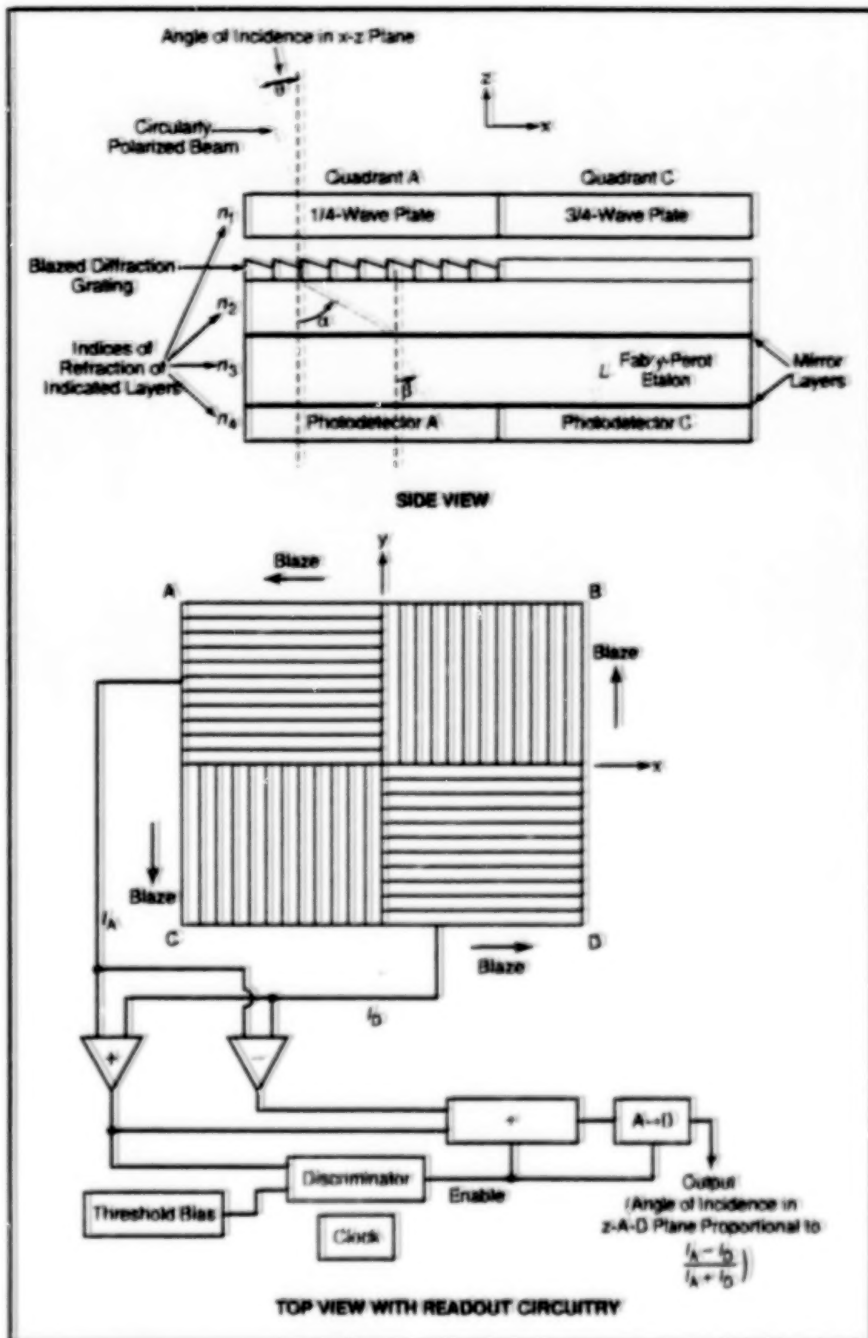
Angular resolution could be as fine as tens of nanoradians.

NASA's Jet Propulsion Laboratory,
Pasadena, California

An optoelectronic device based on interferometry in a resonant microcavity has been proposed for use in measuring the direction of arrival of a circularly polarized beam of light from a beacon laser. In comparison with prior optoelectronic direction sensors, the proposed device would be simple, compact, and lightweight, in that it would contain no moving parts and no imaging optics and could be fabricated from semiconductor crystals. Moreover, it should be possible to integrate readout electronic circuits directly onto the device; these circuits would perform all needed intermediate signal processing to generate electrical output indicative of the angle of incidence of the laser beam on the device. In one potential application, the beacon would be located at one end of a free-space optical-communication link and would be used as a target for aiming a transmitting telescope located at the other end of the link. In another potential application, the beacon could be used similarly as a target for measuring angles precisely in land surveying.

The device, denoted an optical pointer on a chip (OPOC), would be divided into four quadrants, each of which would contain a wave plate in series with a blazed transmission-type diffraction grating, a Fabry-Perot etalon serving as a resonator, and a photodetector (see figure). Each wave plate would transform the circular polarization of the laser beam into the linear polarization optimum for the blaze of the grating in its quadrant. A complete explanation of the principle of operation would entail a great deal of mathematical derivation and, as such, would greatly exceed the space available for this article. In summary:

- The device would exploit the sharp dependence of the transmissivity of a Fabry-Perot resonator on the internal angle (β) of refraction or diffraction.
- The spatial period of the diffraction grating would be chosen so that normally incident light would be diffracted to a desired order inside the resonator at a desired angle β .
- The blazes in the opposite quadrants of the grating would oppose each other in such a manner as to select opposite diffraction orders (e.g., the $+j$ th and the $-j$ th) in opposite quadrants.
- The net result of the aforementioned features is that the currents generated in the photodetectors in opposite quadrants



This Optical Pointer on a Chip would contain several well-known optical components in a unique combination such that the currents generated in the photodetectors in opposite quadrants would respond antisymmetrically to a deviation of the laser beam from normal incidence.

would respond antisymmetrically to a deviation of the laser beam from normal incidence. To a first-order approximation for an angle that is a small fraction of a radian, the angle of incidence in a plane containing the outer corners of quadrants A and D would be proportional to $(I_A - I_D)/(I_A + I_D)$, where I_A and I_D are the photodetector cur-

rents for quadrants A and D, respectively. Similarly, the angle of incidence in the plane containing the corners of quadrants B and C would be proportional to

$$(I_B - I_C)/(I_B + I_C).$$

Several design parameters [e.g., the thickness of the Fabry-Perot etalon, β , the reflectivity (preferably close to 1) of the mirror layers on the etalon, the laser

wavelength, the indices of refraction of the device materials) affect the factor of proportionality and other aspects of the angular response of the device. It has been estimated that resolution of the order of tens of nanoradians could be obtained by suitable choice of design parameters and execution of design by mass-production techniques now in use

in the semiconductor industry.

This work was done by John Sandusky of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to

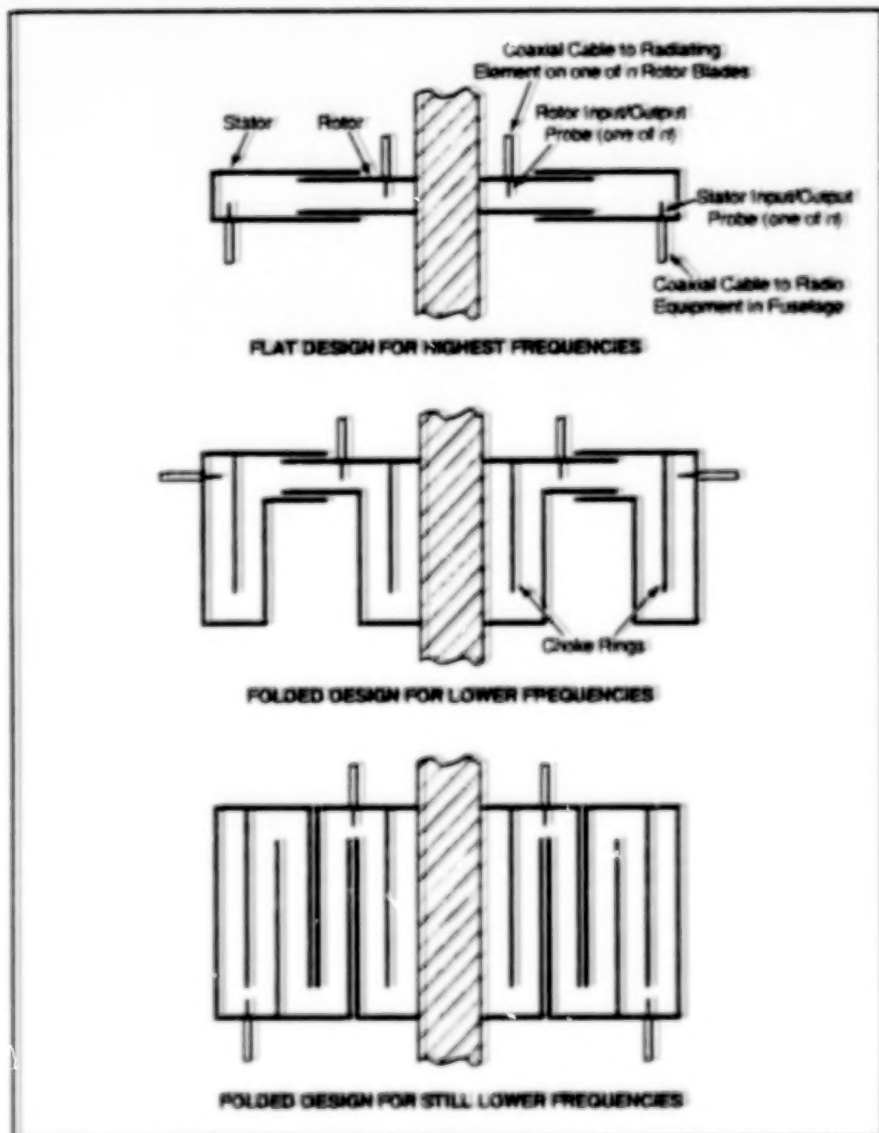
Intellectual Property group
JPL
Mail Stop 202-233
4800 Oak Grove Drive
Pasadena, CA 91109
(818) 354-2240

Refer to NPO-21117, volume and number of this NASA Tech Briefs issue, and the page number.

Communication Antenna in a Helicopter Rotor

The radiation pattern would not turn with the rotor.

NASA's Jet Propulsion Laboratory,
Pasadena, California



The Rotary Radio-Frequency Coupling could be a simple radial waveguide joint with overlapping parallel disks, or perhaps a more-complex radial waveguide joint that could include choke rings.

A proposed communication antenna for a helicopter would feature radiating elements in or on the blades of the main rotor, with a novel rotary radio-frequency coupling between the antenna and the radio equipment in the fuselage. The antenna

would be suitable for communication along both predominantly horizontal paths (e.g., with distant ground stations) and predominantly vertical paths (e.g., with satellites).

The radiating elements would typically be constructed in one of three forms: (1)

The elements could be vertical electric dipoles on the rotor blades; these would transmit and receive in vertical electric polarization. (2) The elements could be horizontal electric dipoles along the blades, in which case they would transmit and receive in horizontal electric polarization. (3) The elements could be horizontal slots on the blades; these would transmit and receive in vertical polarization along horizontal paths, horizontal polarization along vertical paths, and intermediate polarizations along intermediate paths. Horizontal dipoles or slots would ordinarily be preferable to vertical dipoles because they would cause less perturbation of the rotor-blade aerodynamics.

The rotary coupling could be any of several noncontact rotary waveguide joints (see figure). The stator in the rotary coupling would contain a number (n) of input/output probes equal to the number of rotor blades (typically, $n = 5$), positioned at equal angular intervals. The input/output probes in the stator would be connected to a beam-forming network connected via a coaxial cable to the radio equipment in the fuselage. The beam-forming network would be configured so that within the waveguide joint, the radiation would be coupled from the probes (in transmitting) or to the probes (in receiving) in the desired waveguide mode with n -fold azimuthal symmetry. Because the probes would be stationary, this mode would remain stationary.

The rotor part of the rotary coupling would also contain n probes at equal angular intervals. A coaxial cable would couple radiation between each of these probes and the radiating element in or on one of the rotor blades. As the rotor turned, the rotor probes would pass through the stationary n -fold symmetric waveguide mode. This would cause the radio-frequency power coupled between each rotor-blade radiating element and the stationary radio equipment to vary with the instantaneous

angle of rotation, so that the radiation pattern traced out by each radiating element alone during one complete rotation would exhibit n -fold symmetry. However, because there would be n blades, this pattern would be spatially modulated with another n -fold symmetry characteristic of the spatial relationships among the n radiating elements. A basic theoretical analysis shows that the net effect of the rotating and stationary n -fold symmetries would be to produce a predominantly azimuthally symmetric (non-rotating) $2n$ -fold radiation pattern.

The vertical polarization along horizontal paths in the case of horizontal-slot radiating elements would be desirable for communications with ground-based terminals from low altitudes. If either horizontal elec-

tric dipoles or horizontal slots were used, the radiation skyward would be circularly polarized, as would be desirable for communication with satellites.

Because the radiation pattern would not rotate with respect to the airframe, and the rotor blades would not block the radiation, it appears that the proposed antenna would result in much less rotor-blade modulation than is observed when using helicopter antennas of other types. The rotor-blade modulation for this antenna would be limited to that associated with variation in the antenna-element/airframe coupling, with extremes when the center line of the fuselage is aligned with a blade and when it is aligned halfway between two blades. It has been conjectured

that this modulation would be small in comparison with the modulation associated with the usual blockage effects.

Yet another advantage would lie in the variation of the phase of the modal radiation pattern with azimuthal angle. Depending on which mode is excited, the relative phase of a received signal could provide a direct measure of the azimuthal angle of arrival of the signal. Thus, while providing omnidirectional coverage in azimuth, this antenna could also be used for azimuthal direction finding.

This work was done by Ronald J. Pogorzelski of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].
NPO-19803

Improved Array of Switches for Fiber-Optic Communications

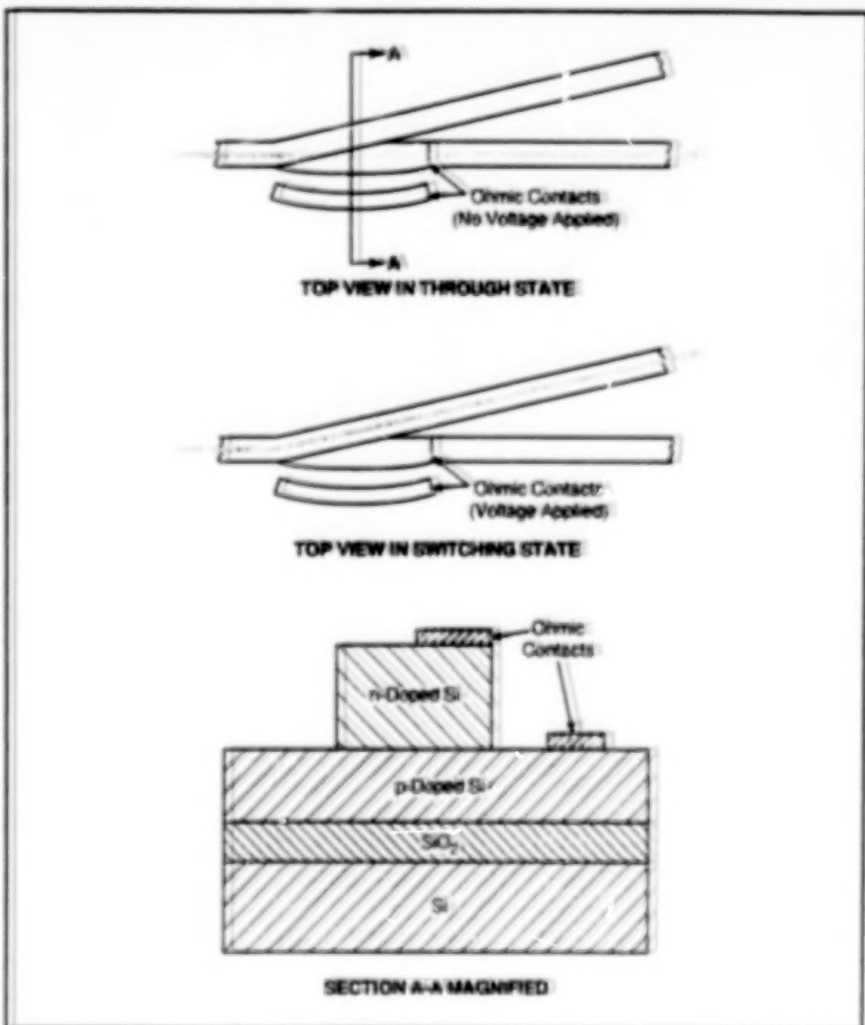
Optical losses would be reduced, relative to prior switches.

A rectangular array of Y-junction electro-optical switches has been proposed as a prototype of reliable, high-speed cross-point switches for fiber-optic-based photonic communication systems. The proposed array would feature a hybrid digital-interference design. The proposed array would be an integrated-optics device, fabricated in the silicon-on-insulator material system; it would be compatible with silicon-based electronic integrated circuits and with up-to-date V-groove packaging.

Some previously developed electro-optical switches are said to be of the interference (more precisely, two-mode interference/single-mode propagation) type, for which the switching characteristic is sinusoidal. The performances of interference-type switches are sensitive to (and can thus be degraded by) imperfections of fabrication and variations of polarization, wavelength, operating voltage, and temperature. Hence, it is difficult to make a high-performance large interference-type switching array.

Some other previously developed electro-optical switches are said to be of the digital type. One subtype includes InP- and GaAs-based symmetric-Y-junction waveguide switches. In the case of an InP switch of this subtype, there are two electrodes on each of the two arms of the Y. When no current is made to flow through the electrodes, the switch behaves as a 3-dB power splitter. When sufficient electrical current is injected via the electrodes on one waveguide arm, the index of refraction of that arm decreases

NASA's Jet Propulsion Laboratory,
Pasadena, California



This **Electro-Optical Switch** (one of many in a rectangular array) would divert light to the branch waveguide when a sufficient current was injected via the electrodes.

by enough that light no longer enters that arm and instead goes entirely into the other arm. Because each waveguide arm is designed to support propagation in only one mode, the light transmission versus the applied current exhibits a step-function characteristic; that is why a switch of this type is denoted a digital optical switch. When the current is turned on, there is an optical loss because (1) the reflection well is tilted because of spreading of the injected current and (2) imperfections of the tips of the Y give rise to radiation and scattering.

The proposed array would contain ridge-waveguide structures. The waveguide ridges would be made of silicon, and the upper and lower cladding (optical-confinement) layers would be made of air and silicon dioxide, respectively. Very low optical-propagation loss has been achieved in such a structure; this is attributable to low optical loss in the air and SiO_2 layers. The silicon wave-guiding layer in the proposed array could be designed with low doping

concentration for low optical absorption.

The principle of operation of the switches in the proposed array would differ from the principles of operation of previously developed electro-optical switches. A switch in this array would exhibit two states—denoted “through” and “switching.” These states are defined in the figure. The through state would involve multimode interference (instead of single-mode propagation). The principle of operation and the design to implement it would significantly reduce (in comparison with an INP switch as described above) the optical loss in through state while retaining the step function switching characteristic essential for effectively digital switching.

The throughput-waveguide portion of each switch would be curved; the precise shape would be chosen to minimize the throughput loss. The electrodes for each switch would be formed in a lateral acceptor-doped/intrinsic/donor-doped (positive/intrinsic/negative (PIN)) configuration

that would suppress spreading of the injected current into the branch waveguide; as a result, the optical loss that would otherwise be associated with current spreading in the switching state could be minimized.

This work was done by Chi Wu and Simak Forouhar of Caltech for **NASA's Jet Propulsion Laboratory**. Further information is contained in a TSP [see page 1].

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to Intellectual Assets Office:

JPL

Mail Stop 202-233

4800 Oak Grove Drive

Pasadena, CA 91109

(818) 354-2240

E-mail: jplgroup@jpl.nasa.gov

Refer to NPO-20755, volume and number of this NASA Tech Briefs issue, and the page number.

Hybrid Electric-Field Sensor

The hybrid electric-field sensor (HEFS) has been proposed for measuring quasi-static electric fields—especially those associated with thunderstorms. The HEFS would combine the relative compactness, low cost, and low power consumption of prior induction-probe-type electric-field sensors with the higher sensitivity of the prior field-mill-type electric-field sensors. The HEFS design would utilize a chopping-electrostatic-shield feature of a field mill over two insulated antennas to overcome the finite time constant and the poor upper-frequency

response of the induction probe and the electric field mill, respectively. The HEFS would be modular in order to accommodate “smart” data-acquisition and communication ports for operation as a battery-powered, stand-alone unit. Optionally, the HEFS could incorporate a barometer, thermometer, and hygrometer, so that it could serve as a portable meteorological station. A network of such stations could transmit digitized measurement data to a central monitoring station. The estimated cost of an HEFS, including communication circuitry, is \$1,000

(based on prices as of year 2001). In contrast, a field mill costs about \$10,000. Moreover, unlike a field mill, an HEFS would consume little enough power that it could be powered by a solar power system backed by rechargeable batteries.

This work was done by Carlos T. Med of Dynacs, Inc., for **Kennedy Space Center**. Further information is contained in a TSP [see page 1]. KSC-12317

Books and Reports

Further Developments Regarding Noise-Reducing Slots in QWIPs

A report presents additional information on the devices described in “Noise-Reducing Slots in Quantum-Well Infrared Photodetectors” (NPO-20518) NASA Tech Briefs, June 2001, page 10. To recapitulate: it was proposed that incorporation of suitably dimensioned crossed slots into quantum-well infrared photodetectors (QWIPs) equipped with two-dimensional surface-grating light couplers would reduce dark currents and increase detectivities. Going slightly beyond that proposal, the report proposes optionally filling the slots with low-

index-of-refraction dielectric material. Going beyond the previous discussion, the report notes that finite-difference solution of the Helmholtz equations for electromagnetic coupling into a slotted QWP leads to the conclusions that (1) the slotted QWP acts as an array of leaky waveguides or weakly coupled cavity resonators; (2) coupling can be maximized by choosing the width, spacing, and index of refraction of the slots to obtain resonance at the desired wavelength of operation; and (3) the coupling in such a case is stronger and more broad-band, relative to the coupling into a non-slotted surface-grating QWP.

This work was done by Daniel Wilson, Sireeth Gunupaki, Sumith Bandaru, and John K. Liu of Caltech for **NASA's Jet Propulsion**

Laboratory. To obtain a copy of the report, “Slotted Quantum Well Infrared Photodetector for Reduced Dark Current and Enhanced Optical Coupling,” see TSP's [page 1].

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

Technology Reporting Office

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Mail Stop 249-103

4800 Oak Grove Drive

Pasadena, CA 91109

(818) 354-2240

Refer to NPO-20585, volume and number of this NASA Tech Briefs issue, and the page number.



Electronic Systems

Hardware, Techniques, and Processes

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- 14 Failure-Reporting Device Concept for Spacecraft and Remote Vehicles
- 14 A Semiautomated Coordinate-Measuring System
- 14 Remote Monitoring and Alarm System

GPS Attitude Determination Using Nonaligned Antennas

Phases of circularly polarized signals are corrected for effects of antenna geometry.

Goddard Space Flight Center,
Greenbelt, Maryland

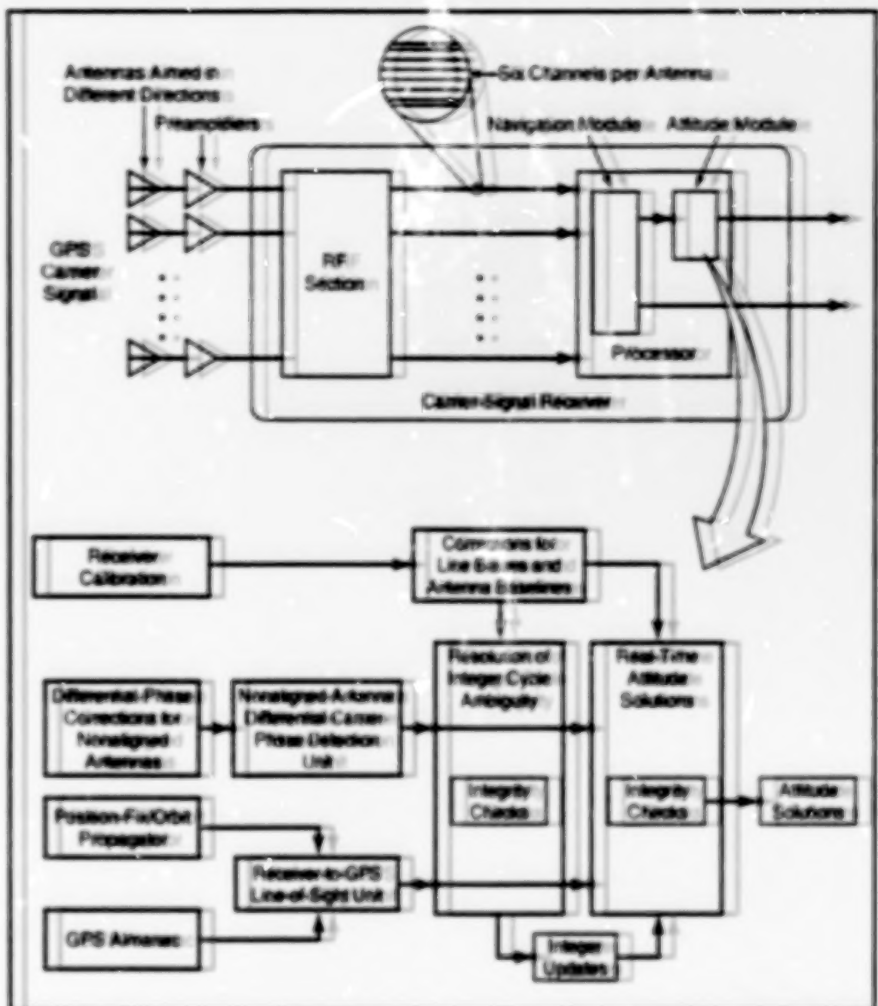
A method of determining the attitude of a vehicle equipped with a Global Positioning System (GPS) receiver with multiple non-aligned antennas has been invented. As used here, "nonaligned antennas" does not signify antennas that lack alignment; rather, it signifies antennas that generally point in different directions (in contradistinction to antennas oriented identically as in prior methods). The method is applicable to a land vehicle, aircraft, spacecraft, ship, or almost any other vehicle.

For the purpose of this or any other method of determining attitude from GPS measurements, the positions and orientations of the antennas with respect to the vehicle and to each other must be known. In general, the attitude of the vehicle, referenced to lines of sight between the vehicle and a set of GPS satellites, is determined from differences among the phases of the GPS carrier signals received by the various antennas.

Prior methods of determining attitude from GPS measurements are based partly on the assumption that the antennas are oriented identically. This assumption simplifies attitude determination in the following way: GPS signals are right-hand circularly polarized (RHCP). In the case of identically oriented antennas, the effects of the circular polarization on the phases of the signals received by all the antennas are equal; therefore, the phase-difference measurements and the attitude determination are unaffected by the circular polarization.

When the antennas are nonaligned, the phase effects of the circular polarization differ among antennas, so that the prior methods cannot be used. In the present method, these effects are taken into account, making it possible to use non-aligned antennas for attitude determination. The major advantage gained through this method is that by using a sufficient number of antennas pointed in different directions, one can maximize the probability that a sufficient number of GPS satellites will be in view at any given time, making it possible to determine the current attitude of the vehicle, regardless of its position, attitude, or state of motion (the vehicle could even be tumbling).

The figure schematically depicts selected aspects of a typical GPS receiver system that implements the present method. Preferably, there are eight antennas and the radio-frequency (RF) section of the receiver can accommodate as many as six GPS channels per antenna. The signals in the



The **Attitude Module** of a GPS Receiver runs software that makes differential-phase corrections for RHCP GPS signals received by nonaligned antennas.

various channels are digitized, then sent to a processor that includes a navigation module and an attitude module. The navigation computations and most of the attitude computations are performed according to conventional GPS methods. The distinct aspect of the present method lies in the software of the attitude module. This software provides phase-difference corrections based on the calculable effects of (1) the known relative positions and orientations of the antennas and (2) the phases of the RHCP GPS signals that they receive.

The primary obstacle to incorporating the RHCP phase-difference corrections into the attitude computations is the fact that the attitude of the vehicle is embedded in expressions of the reference frames of the various antennas. A circular-reasoning condition arises in that to calculate the attitude, it is necessary to know the RHCP corrections, but to calculate the RHCP corrections, the attitude

must be known. If the attitude of the vehicle is already approximately known, perhaps from a prior estimate, the RHCP phase corrections can be estimated and then iterated, along with a new attitude solution, to convergence toward a final attitude solution. If no prior estimate of attitude is available, then an initial estimate can be constructed, for example, by use of the line of sight from each antenna to the source of the strongest GPS signal received on that antenna.

This work was done by Edger Glenn Lightsey of Goddard Space Flight Center. Further information is contained in a TSP [see page 1].

This invention has been patented by NASA (U.S. Patent No. 6,005,514). Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, Goddard Space Flight Center [see page 1]. Refer to GSC-13907.

Failure-Reporting Device Concept for Spacecraft and Remote Vehicles

Unlike aircraft "black boxes," these devices would transmit information to remote receivers.

NASA's Jet Propulsion Laboratory,
Pasadena, California

Failure-reporting devices somewhat similar to the "black box" data recorders on aircraft have been proposed. These devices were conceived for use on spacecraft, but might also be useful on terrestrial autonomous underwater vessels or terrestrial remote exploratory robots. The concept was motivated by the need to learn from mission failures in order to make future missions more failure resistant.

Even more than aircraft "black boxes," the proposed devices would be extremely rugged to survive re-entry into the atmosphere of the Earth as well as impacts substantially harder than those of airplane crashes. Unlike aircraft "black boxes," the proposed devices would not be designed to be retrieved; instead, they would be designed to transmit as much pertinent information as possible to enable analysis to identify specific causes of mission failures.

The design of the proposed devices would follow a "spacecraft within a spacecraft" approach. The device would contain data-handling, telecommunication, power-supply, and structural subsystems. The pri-

mary interfaces between this system and the spacecraft would be power connections and points of access to the spacecraft data bus and/or the spacecraft telemetry-management system. The links between the failure-reporting device and the spacecraft would be subject to severance at any time. However, even while the spacecraft remained intact and functional with the device connected, the device would transmit subcarrier beacon tones that would convey information on the status of the spacecraft during high-risk maneuvers like entry, descent, and landing.

Upon separation from the spacecraft, the device would stop drawing power from the spacecraft power supply and start drawing power from an internal battery. Once separated from the spacecraft, the device would automatically begin transmitting relevant data back to Earth ground stations and/or nearby orbiting spacecraft. A flight-qualified data processor would run the software necessary to record channelized data, set the beacon state, and execute other functions like those of an aircraft

"black box." The level of data processing would depend on the degree to which the data received by the device were summarized and otherwise preprocessed by the spacecraft data-processing system. The most important data would be stored (most likely in a solid-state memory) aboard the device for transmission.

The telecommunications and software subsystem of the device would generate low-rate telemetry signals to transmit stored engineering data. If possible within the processing constraints, summarization software would transmit the most relevant sensor data recorded around the time of the failure. The subcarrier signals could be programmed to correspond to spacecraft failure modes and would provide some indication of status in the event that acquisition of telemetry was not possible.

This work was done by E. Jay Wyatt and John Szijarto of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].
NPO-21942

A Semiautomated Coordinate-Measuring System

The Advanced Payload Transfer Measurement System (APTMS) comprises electromechanical sensors and sensor-output-processing circuits. Designed specifically for measuring offsets between spacecraft payload trunnions and trunnion supports during ground-based payload-transfer operations, the APTMS could be adapted to general measurement of offsets for guiding movement of large objects during assembly of heavy machinery or structures. An electromechanical sensor of the type used in the APTMS was described in "Spherical-Coordinates Encoder Module" (KSC-11973), NASA Tech Briefs, February

2000, page 43. Initially, the sensor outputs were fed via cables to a portable computer for analysis and display. More recently, the sensors and computer were equipped with wireless transceivers capable of communicating in either a time-division- or a spread-spectrum multiple x mode to eliminate the need for cables, thereby contributing to maneuverability and safety in the workspace. An important element of the design and operation of the system is taking calibration measurements and processing of these measurements by curve-fitting software to piecewise-linear offsets to correct for systematic errors in raw sensor outputs

in order to obtain accuracy within 0.05 in. (≈ 1.3 mm) at distances ≤ 40 in. (≈ 1 m).

This work was done by Felix A. Soto Toro of Kennedy Space Center and Wasfy Mikhael of the University of Central Florida. Further information is contained in a TSP [see page 1].

Inquiries concerning rights for the commercial use of this invention should be addressed to the Technology Programs and Commercialization Office, Kennedy Space Center, (321) 867-4879. Refer to KSC-12204/3/195.

Remote Monitoring and Alarm System

The Remote Monitoring and Alarm System (RMAS) is a system of electronic hardware and software for monitoring of fiber-optic video transmission equipment at Kennedy Space Center (KSC). The RMAS could also monitor other equipment that generates discrete contact closures and/or analog voltages. The hardware includes

multiple remote terminal units (RTUs) that are collocated with, and gather both discrete and analog information from, the monitored equipment, and convert this information to RS-232 data streams. The RTUs are connected via point-to-point long-haul modem circuits to a 96-port code-activated switch (CAS), that, in turn,

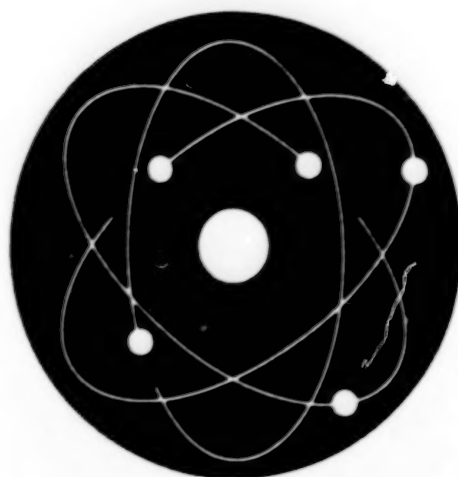
connects specific RTUs to a monitoring computer workstation. Polling software running on the workstation periodically gathers data from each RTU and stores the data for processing by network-management software, which also runs on the workstation. The network-management software analyzes the data to generate a

graphical representation of the fiber-optic video transmission equipment, with indications of any alarm conditions. Each RTU contains custom firmware that governs communication with the polling software and that, upon command by a user,

implements diagnostic routines. A Simple Network Management Protocol agent links the polling software to the network-manager software via a custom management information base.

This work was done by Philip Gvozdz,

Matthew Smisor, and William Toler of Kennedy Space Center and Chris Kerios, Robert Chiodini, Pamela K. Schmidt, and Robert Swindle of Dynacs, Inc. Further information is contained in a TSP [see page 1].
KSC-12314



Physical Sciences

Hardware, Techniques, and Processes

- | | |
|----|---|
| 19 | Making Hydrogen by Electrolysis of Methanol |
| 20 | Miniature NMR Spectrometers Without Magnets |
| 21 | Aircraft-Mounted Cloud-Water-Content Probe |

Making Hydrogen by Electrolysis of Methanol

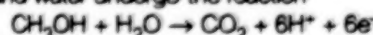
The cost is about half that of making hydrogen by electrolysis of water.

NASA's Jet Propulsion Laboratory,
Pasadena, California

Scientists at NASA's Jet Propulsion Laboratory are developing apparatuses for electrolysis of methanol to produce pure hydrogen for use at industrial sites, in scientific laboratories, and in fuel cells. The state-of-the-art onsite hydrogen generators now in use are based on electrolysis of water to produce hydrogen, with oxygen as a byproduct that has no commercial value in this context. The developmental methanol electrolyzers consume less than half the electrical energy of water electrolyzers in producing a given amount of hydrogen. Even when the cost of methanol is included, the cost of producing hydrogen by electrolysis of methanol is still only about half that of producing hydrogen by electrolysis of water.

Figure 1 schematically illustrates a methanol-electrolysis apparatus. The heart of the apparatus is an electrolysis cell that contains a unitary membrane-electrode structure. Typically, this structure comprises a solid electrolyte in the form of a proton-conducting polymeric membrane, with a catalytic anode (e.g., containing a Pt/Ru catalyst) deposited on one side and a catalytic cathode (e.g., containing Pt or Pd as the catalyst) deposited on the other side.

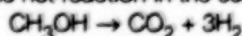
An aqueous solution of methanol is circulated past the anode, where methanol and water undergo the reaction



The hydrogen ions pass through the membrane to the cathode, where they are reduced to hydrogen molecules in the reaction



Thus, the net reaction in the cell is



with carbon dioxide liberated on the anode side and hydrogen liberated on the cathode side. Because the membrane is not totally impermeable to water and methanol, traces of these substances pass through along with the protons. However, the water and methanol can easily be removed from the hydrogen stream by use of a molecular sieve, as is routinely done to remove traces of water and oxygen from hydrogen streams produced in water electrolyzers.

If the solid-electrolyte membrane in the cell is made of Nafion™ (or equivalent) perfluorosulfonic acid-based proton-conducting polymer, then the cell can be operated in the temperature range from 5 to 120 °C. The concentration of methanol in the aqueous solution can range from 0.1 to 8 molar.

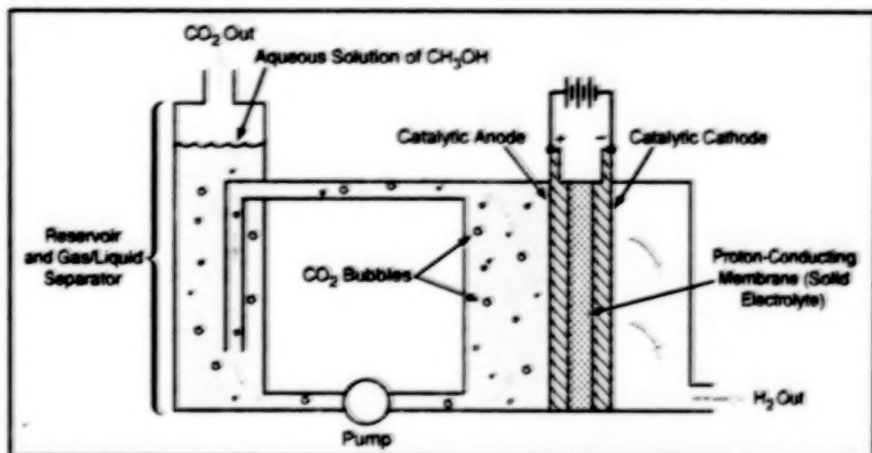


Figure 1. Methanol is electrolyzed to hydrogen (the main product) and carbon dioxide (the byproduct). The carbon dioxide is vented, while the hydrogen is purified with a molecular sieve to remove traces of water and methanol before use.

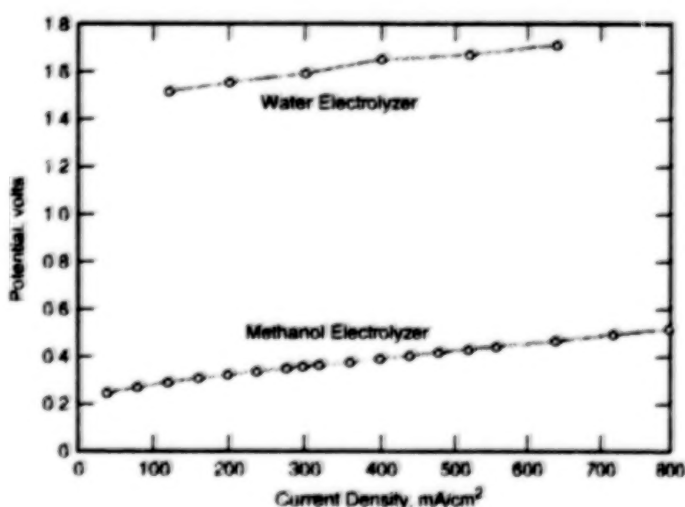


Figure 2. Less Voltage is needed to electrolyze methanol than to electrolyze water at the same current density, as indicated by these plots of data from an experiment with a prototype methanol electrolyzer and a commercial water electrolyzer.

The membrane is the electrolyte, and it is not necessary to acidify the solution to make it electrically conductive.

The theoretical operating potential of the cell is 0.02 V, though in practice, a useful amount of electrolysis is not achieved until the potential is raised to 0.3 V. In contrast, the potential needed to electrolyze water is more than 1.4 V, even in the most efficient electrolyzers. As shown in Figure 2, the potential needed to obtain a given current density in electrolysis of methanol is more than 1 V below the potential needed to obtain the same current density in electrolysis of water. The electrical power consumed in electrolysis is reduced proportionately.

This work was done by Sekharipuram Narayanan, William Chun, Barbara Jeffries-

Nakamura, and Thomas I. Valdez of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to

Technology Reporting Office

JPL

Mail Stop 122-116

4800 Oak Grove Drive

Pasadena, CA 91109

(818) 354-2240

Refer to NPO-19948, volume and number of this NASA Tech Briefs issue, and the page number.

Miniature NMR Spectrometers Without Magnets

These spectrometers would be used to characterize ferromagnetic minerals.

NASA's Jet Propulsion Laboratory,
Pasadena, California

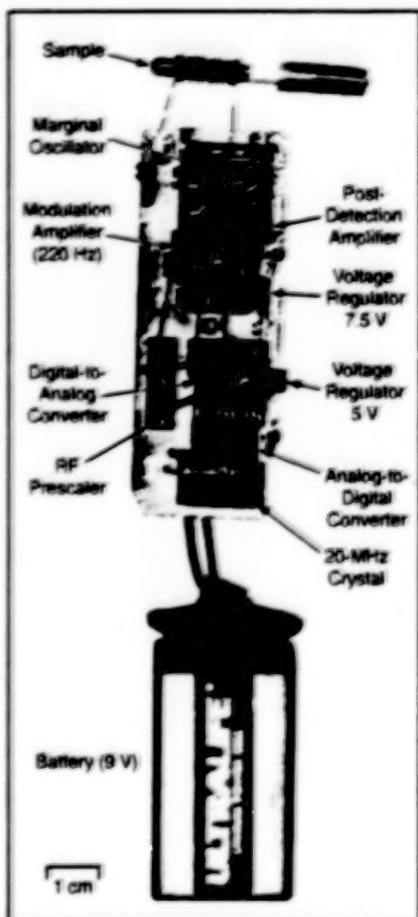


Figure 1. This Miniature NMR Spectrometer has a mass of only 65 g (this includes the battery) and consumes a power of only 0.2 W.

Miniature, lightweight nuclear-magnetic-resonance (NMR) spectrometers suitable for characterizing ferromagnetic minerals in the field are undergoing development. In previously developed miniature NMR spectrometers, more than half the weight is contributed by permanent magnets. The present developmental miniature NMR spectrometers can be made much lighter because they do not contain permanent magnets: Unlike other NMR spectrometers, they are designed to operate without applied magnetic fields; instead, they exploit the natural magnetic fields of the mineral phases to be studied.

Figure 1 shows a prototype instrument of this type designed to exploit the natural magnetic fields in minerals that contain iron. These fields give rise to nuclear magnetic resonance of the isotope ^{57}Fe at frequencies in the approximate range of 60 to 74 MHz. Resonances occur at specific fre-

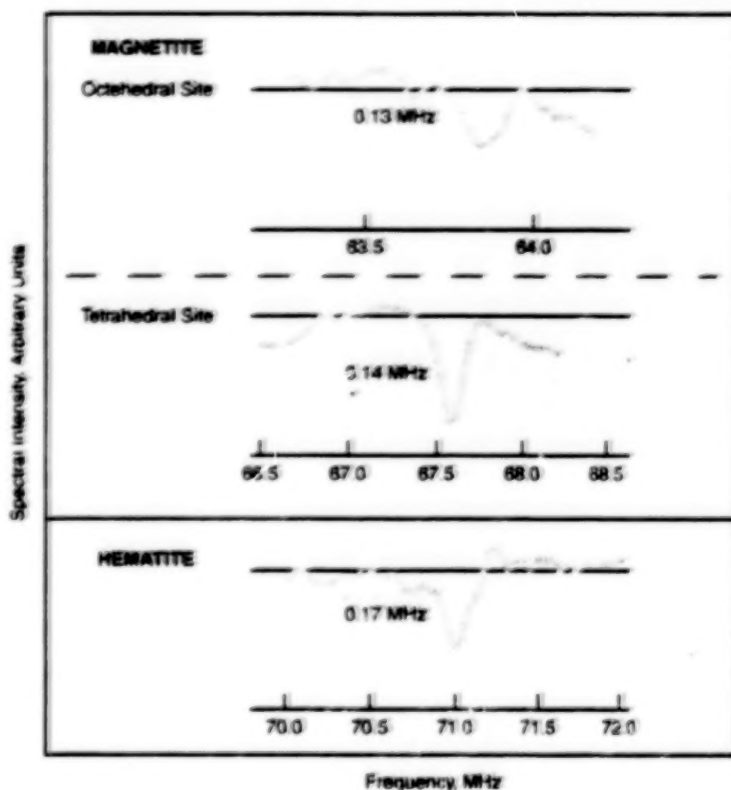


Figure 2. These NMR Spectra of specimens of magnetite and hematite were obtained by use of the instrument shown in Figure 1.

quencies associated with mineral phases of interest. For example, magnetite (Fe_3O_4) exhibits a resonance at 63.8 MHz for $^{57}\text{Fe}^{3+}$ ions in octahedral sites (coordination with oxygen atoms) and another resonance at 67.6 for $^{57}\text{Fe}^{3+}$ at tetrahedral sites.

This instrument includes a marginal oscillator, the frequency of which is determined mainly by tuning capacitors, two varactors, and the NMR sample coil, in which a mineral specimen is placed. During operation, the frequency is swept slowly by use of one varactor, and is modulated at a rate of 110 Hz by use of the other varactor. The instrument also includes a digital-to-analog and an analog-to-digital converter and a microprocessor that communicates with an external laptop computer, generates frequency-sweep and modulation signals, samples the output from the oscillator, and performs synchronous detection.

The instrument is connected with the computer via a telephone (RS232) cable. Such parameters as the scan range, scan

rate, number of averages, and time constant can be set through the computer keyboard. Spectral data can be displayed on the computer screen. The software in the computer includes routines for processing data to estimate concentrations of mineral phases of interest.

The performance of the instrument was demonstrated in NMR measurement experiments on two mineral specimens: one that contained magnetite in chlorite schist mixed with magnetically inert particles and one made of hematite ($\alpha\text{-Fe}_2\text{O}_3$). The spectra obtained from these specimens (see Figure 2) show the expected magnetite resonances and a hematite resonance at about 70.8 MHz.

This work was done by Soon Sam Kim, Narayan Mysoor, and Christopher Ulmer of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].
NPO-20106

Aircraft-Mounted Cloud-Water-Content Probe

This relatively simple instrument contains no heater or pump.

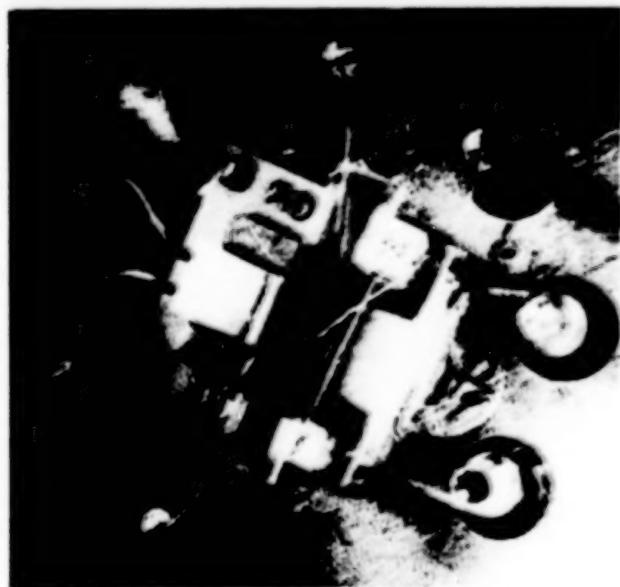
NASA's Jet Propulsion Laboratory,
Pasadena, California



AIR-SAMPLING PROBE (FRONT VIEW)



AIR-SAMPLING PROBE (REAR VIEW)



SURFACE-ACOUSTIC-WAVE HYGROMETER

The Air-Sampling Probe feeds an aerodynamically heated sample stream to the surface-acoustic-wave hygrometer.

An aircraft-mounted instrument for high-resolution, *in situ* measurement of the abundances of liquid water and ice in clouds is undergoing development. This instrument is intended to overcome the disadvantages of instruments developed previously for the same purpose. The dis-

advantages include various combinations of complexity, dependence on heaters and/or pumps, insensitivity to ice crystals, or dependence on droplet/crystal size. The present instrument is relatively simple, does not include a heater or a pump, and is expected (when fully developed) to

be sensitive to both water droplets and ice crystals of any size.

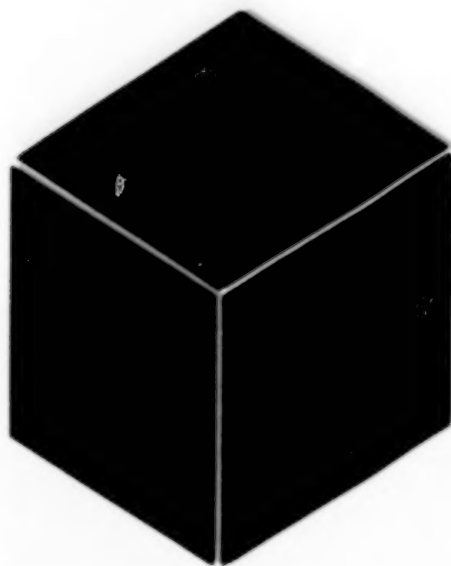
In principle, the fully developed version of the instrument would contain (1) a first air-sampling probe based a total-temperature probe, (2) a second air-sampling probe that would reject water droplets and ice crystals, and (3) two fast-reading electronic hygrometers — one for each probe. A simplified prototype of the instrument has been built from a modified commercial total-temperature probe and a surface-acoustic-wave hygrometer (see figure).

By virtue of its total-temperature feature, the first air-sampling probe would bring the incident airflow to rest (except for a slow internal sampling flow), thus raising the temperature of the sampled air. This aerodynamic heating would cause entrained water droplets and ice crystals to evaporate. The sample stream containing the water vapor generated by aerodynamic heating would be routed to the associated first hygrometer, which would thus be made to measure the total water content (vapor, liquid, and ice) of the ambient air.

The sample stream from the second probe would be routed to the associated second hygrometer, but, unlike the sample stream from the first probe, this stream would not contain the vapor from the water droplets and ice crystals; that is, its vapor content would consist solely of the ambient-air vapor. Then one could subtract the vapor reading of the second hygrometer from the vapor+liquid+ice reading of the first hygrometer to determine the liquid+ice content.

Of course, the cloud-water-content determinations made by use of the instrument depend largely on the assumption that all of the droplets evaporate and all of the ice crystals sublimate in the first probe as a result of aerodynamic heating (and, possibly, of impact upon the probe wall). It is planned to assess the validity of this assumption in tests in a wet wind tunnel.

This work was done by Flavio Noca and Michael Hoenk of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].
NPO-20767



Materials

Hardware, Techniques, and Processes

- 25 Using Polyimide Tape To Mask Against Reactive-Ion Etching
- 25 Fabricating Sapphire Optical Fibers for High-Temperature Use
- 26 Improvements in the Use of Water Washes in Testing for NVR

Using Polyimide Tape To Mask Against Reactive-Ion Etching

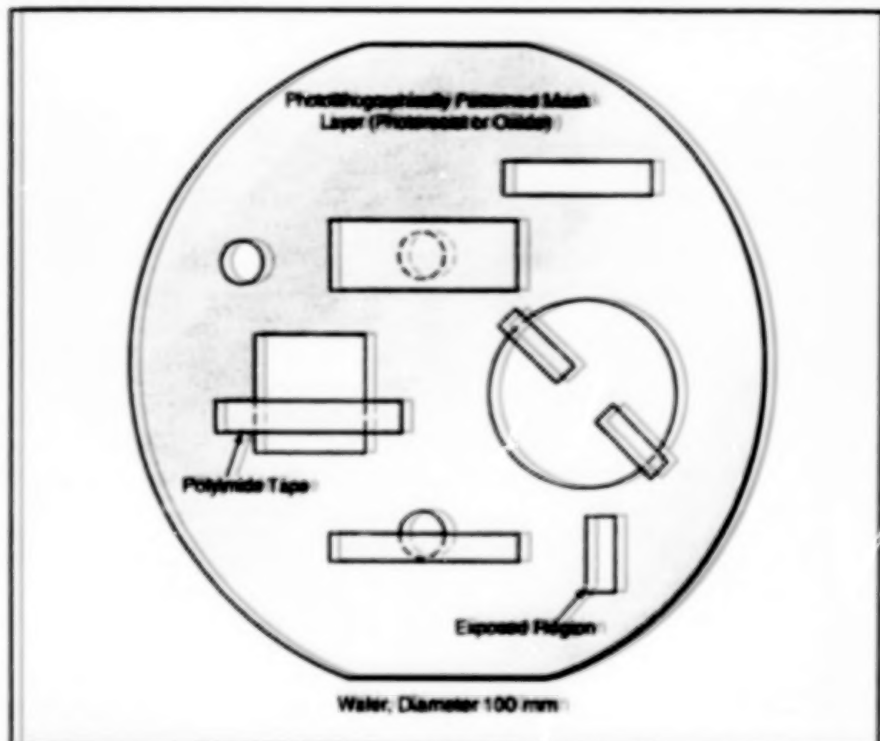
This technique is cheap, simple, and effective.

NASA's Jet Propulsion Laboratory,
Pasadena, California

Polyimide tape (Kipton™ or equivalent) has been found to be effective as a material for masking selected areas of a semiconductor wafer that is about to be processed in a reactive-ion etching (RIE) apparatus. The conventional etch-resistant masking materials for protecting selected areas against etching are photoresists and oxides. These materials are patterned into masks by standard photolithographic techniques. The use of polyimide tape is an inexpensive option that provides additional flexibility for increasing the protection of some areas and for implementing last-minute design changes without having to incur the high cost of making optical masks for photolithography.

The tape is cut to fit the areas that are to be protected against etching; then secured to the wafer by use of its own adhesive backing (see figure). The tape is smoothed down to remove pockets of air that would otherwise become trapped between the wafer and the adhesive. The tape is thin enough ($\approx 50 \mu\text{m}$) that it can easily be made to conform to previously patterned changes in surface height. When the RIE process is finished, the tape is simply pulled off.

In experiments, polyimide tape proved effective in preventing RIE of masked areas. Specimens of tape that were exposed to RIE and vacuum for as long as 3 hours exhibited no measurable change in



Pieces of Polyimide Tape are applied to areas designated to be protected (or additionally protected) against RIE. During the RIE process, the ions are incident along the perpendicular to the plane of this drawing.

thickness, no loss of adhesion, no changes in color, and no melting or other surface changes.

This work was done by Stephen Vargo of Caltech for NASA's Jet Propulsion

Laboratory. Further information is contained in a TSP [see page 1].
NPO-20598

Fabricating Sapphire Optical Fibers for High-Temperature Use

Polycrystalline cladding layers are formed on sapphire cores.

John H. Glenn Research Center,
Cleveland, Ohio

A process for the fabrication of coated sapphire multimode optical fibers has been developed. Sapphire multimode optical fibers are suitable for use as embedded sensors for measuring mechanical and thermal stresses and strains in material specimens at temperatures up to about 1,500 °C.

The core of each optical fiber of this type is made of optical-grade single-crystal sapphire (which is basically an allotrope of alumina). The sapphire core is clad with a layer that has an index of refraction smaller than that of sapphire, in order to confine propagating optical signals predominantly in the core and limit attenuation at the surface of the core. The cladding material preferred for thermal durability and for chemical compati-

bility with the core is polycrystalline alumina; however, one or more other optical materials (e.g., SiO_2 , MgO , Al_2SiO_5) could be used for cladding. The cladding should be at least a few tens of microns thick, the exact required thickness depending on the optical properties needed for a specific application. The cladding is coated with an outer protective layer of SiC , ZrO_2 , Ta_2O_5 , HfO_2 , or other strong, high-temperature-resistant material.

The techniques used to apply the cladding and protective layers are critical to the success of the fabrication process. The techniques and the fabrication sequence are chosen to ensure adhesion between adjacent layers. Although the process admits of a number of variations, the following steps

are typical:

1. The surface of a sapphire optical fiber is prepared by cleaning in hydrochloric acid followed by rinsing in distilled water.
2. Alumina particles no larger than about 20 nm are suspended in a suitable monomer (e.g., acrylic acid) and a suitable accelerator and initiator are added to the suspension.
3. The fiber is immersed in the suspension for about half an hour to allow a thin sublayer of polymer and alumina particles to begin to form on its surface, and the fiber is allowed to stand out of the suspension for another 24 hours, during which time the monomer polymerizes. All of the foregoing steps take place at

room temperature.

4. The coated fiber is heated to a temperature of 600 °C to remove the polymeric binder, leaving the alumina particles in place.
5. The coated fiber is heated further to a temperature between 1,300 and 1,500 °C for a time between 10 and 60 minutes, in order to sinter the alumina particles around the sapphire core. The precise temperature-vs.-

time sintering schedule is chosen to suit the intended application.

6. Steps 2 through 5 are repeated, as needed, in order to accumulate cladding sublayers to the required cladding-layer thickness.
7. A suspension of particles of the protective material is prepared as in step 2, then applied to the fiber and consolidated as in steps 3 through 5.

This work was done by Don J. Roth of

Glenn Research Center and Mahmoud A. El-Shor, Ibrahim L. Kamei, and Frank K. Ko of Drexel University. Further information is contained in a TSP [see page 1].

Inquiries concerning rights for the commercial use of this invention should be addressed to: NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fiedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LBW-17054.

Improvements in the Use of Water Washes in Testing for NVR

Effectiveness of washing and sensitivity of detection are increased.

John F. Kennedy Space Center,
Florida

Some improvements have been made to enhance the role of water as a test solvent for determining the amount of hydrocarbon nonvolatile residue (NVR) present on an item of hardware that is required to be totally or nearly devoid of such residue. Water is now used as an NVR-testing solvent because (1) even high-molecular-weight hydrocarbon greases are at least slightly soluble in water; (2) water is safer and less expensive than are chlorofluorocarbon solvents (in particular, 1,1,2-trichloro-1,2,2-trifluoroethane (also known as CFC-113)), which was used previously in testing for hydrocarbon NVR; and (3) CFC solvents are expensive and are now recognized as environmentally harmful.

The present improvements address two major aspects of the NVR-testing problem: (1) increasing the efficiency of removal of NVR from hardware by use of water and (2) increasing the sensitivity of measuring

the concentration of NVR dissolved in the water. Prior to these improvements, it was known that when small parts are subjected to ultrasound in a water bath and NVR is present, the amount of NVR dispersed into the water is sufficient to enable measurement of the concentration of the dissolved NVR by the total-organic-carbon (TOC) method.

The present improvements extend the applicability of water-wash NVR testing to parts too large to fit in an ultrasonic bath. The efficiency of removal of NVR from a large part can be increased somewhat by use of steam or high-pressure spray of water, with or without a gas mixed in. However, the technique found to be most efficient (and least dependent on the size of the part) is spraying water on the surface of the part from an ultrasonic nozzle.

The increase in the sensitivity of measurement is achieved by concentrating the

NVR from the wash water before attempting the measurement. For this purpose, all of the wash water is made to flow through a bed of silica gel. During this flow, a significant portion of the dissolved NVR becomes adsorbed onto the silica gel particles. Then part or all of the silica gel is analyzed by the TOC method. Tests have shown that by use of both ultrasonic spraying of water and measurement of the TOC of silica gel through which the wash water has passed, it is possible to measure areal concentrations of NVR as low as 0.05 mg/ft² (=0.5 mg/m²) on the surfaces of parts under test.

This work was done by Christian Clausen III of the University of Central Florida for Kennedy Space Center. Further information is contained in a TSP [see page 1].
KSC-12129



Computer Programs

Machinery

- 29 Software for Simultaneous Control of Three Magnetic Bearings

Mathematics and Information Sciences

- 29 Software for Automated Planning of Spacecraft Missions
- 29 Generalized-Time-Line Program for Planning and Scheduling
- 29 Program Uses Terrain-Image Data To Locate Safe Landing Site

Computer Programs

Machinery

Software for Simultaneous Control of Three Magnetic Bearings

Five-Axis, Three-Magnetic-Bearing Control Code (FATMaCC) is a C++-language computer program for controlling a magnetic thrust bearing in one degree of freedom and two magnetic radial bearings, each in two degrees of freedom. These bearings levitate a vertical-axis rotor for experiments on the effects of vibrations on turbomachinery. When executed on a 1-GHz processor, FATMaCC can control the bearing/rotor motions in either a decentralized or a centralized (modal-control) manner at a loop time of 56 μ s. Through keyboard entries, the user can modify such bearing parameters as stiffness, damping, and bias. A module in the program generates signals that can be superimposed on the radial-bearing x- and y-axis control signals to generate forces that excite rotor vibrations. There is an option to modulate the radial bearing control signals with cosine and sine functions, to make the radial excitation force vector rotate about the nominal central bearing axis. There is also an option to excite rotor rigid-body modes; depending on the polarities of the excitation signals applied to the radial bearings, either the bounce or the tilt mode is excited.

This program was written by Carlos R. Morrison of **Glenn Research Center**. Further information is contained in a TSP [see page 1].

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17293.

Mathematics and Information Sciences

Software for Automated Planning of Spacecraft Missions

An artificial-intelligence computer program generates and evaluates plans for spacecraft missions subject to constraints associated with spacecraft designs. The input to the program includes spacecraft design para-

eters (e.g., slew rates and battery capacities) and mission parameters (e.g., requested scientific observations, frequency of communication passes, and trajectory). The program generates a mission-activity plan for attaining mission goals without violating constraints (e.g., for making all desired observations within the available time). The program makes it possible to perform rapid evaluations of multiple candidate designs against a given mission scenario by generating plans for each design and automatically evaluating them against objective criteria. Alternatively, the program can also be used to perform "what-if" evaluations. This program can be used early in the spacecraft-design and spacecraft-mission-planning process, thereby helping to ensure that a spacecraft design and mission plan are consistent with each other; more specifically, the program can show how a given design can be expected to perform in a given mission scenario, and on the basis of the program output, one can modify the design and/or the mission to improve performance.

This program was written by Steve Chien, Barbara Engelhardt, Darren Mutz, Russell Knight, Gregg Rabideau, Robert Sherwood, Ben Smith, Colette Wilkow, and Jason Willis of **Caltech for NASA's Jet Propulsion Laboratory**. Further information is contained in a TSP [see page 1].

This software is available for commercial licensing. Please contact Don Hart of the **California Institute of Technology** at (818) 393-3425. Refer to NPO-21000.

Generalized-Time-Line Program for Planning and Scheduling

Generalized Timelines API is a computer program that provides (1) a means of representing arbitrary real-world state and resource information for use in planning, scheduling, and plan- and schedule-executing software and (2) an application-programming interface (API) that accelerates the development and validation of the software. In prior time-line programs, constraints had not been regarded as parts of time lines, and it was difficult to represent constraints. For the present program, a time line is defined as a representation of the actual and/or predicted value(s) of a variable and a set of constraints on the variable, both at successive intervals of time. The program (1) enables assignment of values to variables and modeling of the constraints on the variables, all as functions of time; (2) makes it possible to determine whether the values are consistent with the constraints; and (3) provides "hooks" to the search space repre-

mented by the variables for the purpose of optimizing plans. This program enables computer-programming specialists to engage in research on, and development of, scheduling application programs separately from the efforts of other specialists to implement time lines specific to their domains of expertise. In comparison with prior software of the same type, this program is representationally sufficient for more domains.

This program was written by Steve Chien, Russell Knight, Kim Gostelow, Tom Starbird, Gregg Rabideau, and Robert Sherwood of **Caltech for NASA's Jet Propulsion Laboratory**. Further information is contained in a TSP [see page 1].

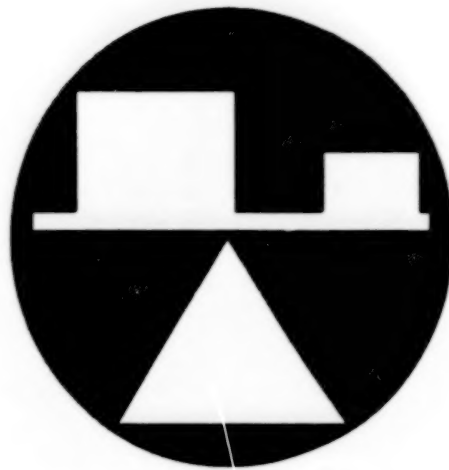
This software is available for commercial licensing. Please contact Don Hart of the **California Institute of Technology** at (818) 393-3425. Refer to NPO-21022.

Program Uses Terrain-Image Data To Locate Safe Landing Site

A computer program under continuing development strives to locate a safe landing site for a spacecraft through real-time processing of image data acquired by a video camera aimed at the terrain below while the spacecraft descends. The program might also be useful for aiding the selection of a landing site for an unpowered helicopter or other unpowered aircraft capable of slow vertical or nearly vertical descent. The program implements two main algorithms: a texture-based landing-site-selection algorithm and a landing-site slope-estimation algorithm. The texture-based algorithm analyzes spatial variations in image brightness to identify candidate sites that are acceptably smooth and free of large rocks. The slope-estimation algorithm computes the slope on the basis of the perspective relationships between two images of the same terrain area acquired from successive positions along the descent trajectory. Because the slope is a very important factor for safe landing and for mobility of a robotic exploratory ground vehicle to be deployed from the spacecraft after landing, the slope-estimation algorithm includes an error-analysis subalgorithm.

This program was written by Yang Cheng, Andrew Johnson, Larry Matthies, and Aron Wolf of **Caltech for NASA's Jet Propulsion Laboratory**. Further information is contained in a TSP [see page 1].

This software is available for commercial licensing. Please contact Don Hart of the **California Institute of Technology** at (818) 393-3425. Refer to NPO-30268.



Mechanics

Hardware, Techniques, and Processes

- 33 Flight Research on Supersonic Laminar Flow
- 33 Hexfoil Rotary Flexures
- 34 Algorithm Computes Kinematics of a Rover on Rocky Terrain
- 35 Crowned Races for Crossed Roller Bearings
- 36 Improved Flange Design for Cryogenic Vacuum O-Ring Seals

Flight Research on Supersonic Laminar Flow

Flow over a suitably designed airfoil can remain largely laminar, even at supersonic speed.

Some airfoil designs have been shown by theory and small-scale tests to be capable of passively maintaining laminar flow at supersonic speeds. More recently, flight tests have proven that these designs can maintain large runs of laminar flow at higher Reynolds numbers in harsh flight environments. The flight tests were conducted for the purposes of observing laminar flow at speeds up to mach 2.0 and determining the conditions under which laminar flow breaks down.

Flight tests were performed on an F-15B airplane equipped with a laminar-flow test article — essentially, a small half wing mounted vertically (see figure). The airplane was also equipped with an infrared camera for observing the test article flow. In effect, the camera measures the local surface temperature of the test article, which temperature varies with the state of the boundary-layer flow. The portion of the surface covered by a turbulent boundary layer is warmer than that covered by a laminar boundary layer — a consequence of its higher wall recovery temperature as well as greater convection of the turbulent layer with the free-stream flow. Hence, in the infrared image, the surface in the turbulent-flow region appears brighter than that in the laminar-flow region.

The test article was fabricated from aluminum with an insulating layer covering all but the first 3 to 4 in. (about 7.5 to 10 cm) in from the leading and trailing edges. A splitter plate was installed at the root of the test article to minimize the effect of disturbances from the bottom of the airplane on the flow about the test article and to better simulate a full-span wing.

Laminar flow was observed up to full chord on the outer third of the span of the



The Boundary of the Transition from laminar to turbulent flow is visible in an infrared image of the test article taken during supersonic flight.

Dryden Flight Research Center,
Edwards, California

test article and up to approximately 80 percent of chord over the inner two-thirds of the span. The laminar flow was found to be capable of penetrating weak shock waves, but was typically terminated by strong shock waves. The strongest shock wave incident on the test surface appeared to emanate from the camera pod, which was located on an armament rail of the airplane.

For future flights, the test article will be instrumented with surface-pressure gauges and thermocouples to obtain more detailed data. Also, the video data-recording system will be updated to enable it to record the full 12-bit digital images from the camera. A contemplated subsequent program would use a larger test article that would permit assessment of effects of greater Reynolds numbers.

This work was done by Daniel W. Banks of Dryden Flight Research Center and Richard R. Tracy, James D. Chase, and Rodney Schapel of Reno Aeronautical Corporation, a subsidiary of Directed Technologies, Inc. Further information can be obtained from Daniel Banks (telephone no. (866) 276-2921 or e-mail dan.banks@dfrc.nasa.gov).

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to Richard R. Tracy, Ph.D., President Reno Aeronautical Corporation 3000 Old Ranch Rd. Carson City, NV 89704-9542 Tel. No.: 775-883-8410 E-mail: tracy@renoaero.com

Refer to DFC-00-22, volume and number of this NASA Tech Briefs issue, and the page number.

Hexfoil Rotary Flexures

These devices would afford high accuracy of centration.

Hexfoil rotary flexures have been proposed as pivots suitable for use in precise optical instruments. In the application that inspired the hexfoil concept, there is a requirement for a limited-rotation mirror gimbal that would maintain, with unprecedented accuracy, coincidence among the axes of rotation and a fiducial mark on the mirror, over the entire range of rotation.

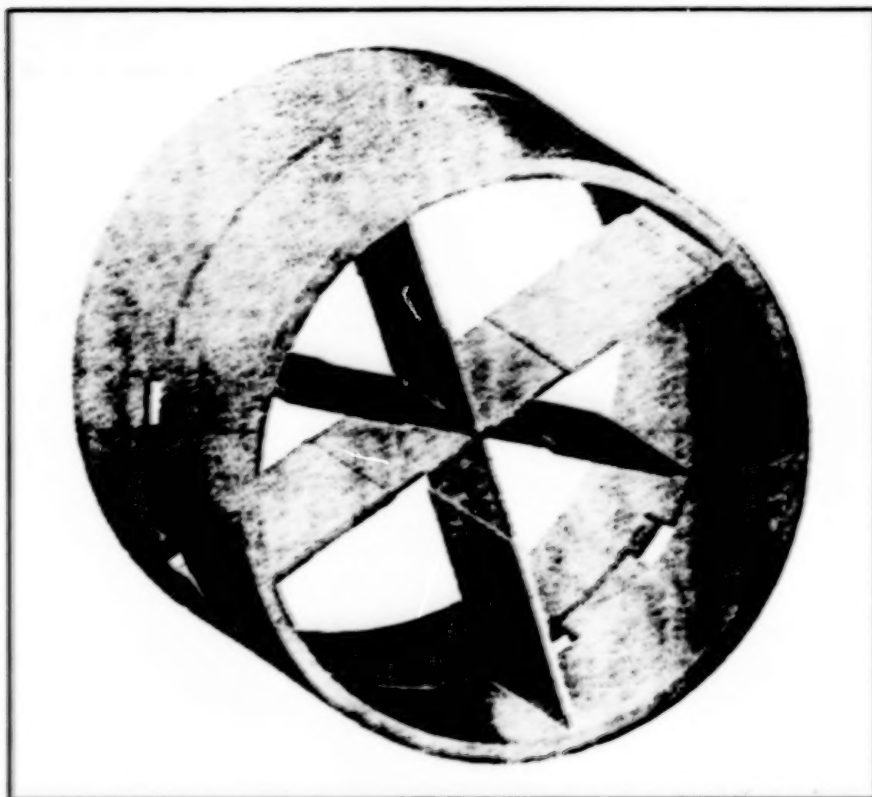
Theoretically, a hexfoil rotary flexure could satisfy this requirement.

A hexfoil rotary flexure would offer the following advantages over a nominally equivalent commercial rotary flexure:

- A hexfoil rotary flexure would maintain a static center of rotation; in other words, it would be subject to no more than negligible drift of the center of rotation.

NASA's Jet Propulsion Laboratory,
Pasadena, California

- The ratio between lateral stiffness and rotational stiffness (this ratio is regarded as a figure of merit for a flexural pivot) would be much greater. Thus, a hexfoil would approximate an ideal pivot more closely.
- An optimized hexfoil rotary flexure could withstand a lateral load greater than that for any similarly sized commercial flexural pivot.



A Hexfoil Rotary Flexure would feature a favorable load-bearing configuration and a high degree of symmetry, such that the application of torque about the cylindrical axis would result in exceptionally pure rotation, even in the presence of axial and lateral loads.

- A hexfoil rotary pivot would be made from a single piece of material. The monolithic nature of this device would ensure the highest reliability.

The hexfoil rotary flexure is related to the device described in "Trefoil Rotary Flexure" (NPO-20228) NASA Tech Briefs, August 1998, page 43. In comparison with a trefoil pivot, a hexfoil pivot would have twice the angular range, while sacrificing some lateral stiffness and load capability. A hexfoil pivot could be designed as a drop-in replacement for a standard Lucas (or equivalent)

pivot, inasmuch as it has the same type of interface.

A hexfoil pivot (see figure) would include two coaxial hollow circular cylinders that would constitute a rotor and stator, respectively. From each cylinder, three flexural elements in the form of thin plates spaced at equal circumferential intervals would extend radially inward, terminating at approximately the axis of rotation. More precisely, the plates attached to each cylinder would be parallelograms with bases equal to the length of the cylinder, radial heights approx-

imately equal to the inner radius of the cylinder, and an axial slant distance of approximately half the length of the cylinder. Thus, in effect, the three flexural elements from each cylinder would terminate in a line segment of length equal to that of the cylinder, coincident with axis of rotation, displaced axially from the cylinder by half the length of the cylinder.

To complete the characterization, it should be mentioned that the on-axis flexure termination for each cylinder would be displaced axially toward the other cylinder, such that the flexure terminations for both cylinders would coincide. Furthermore, the flexural elements for the two cylinders would be "clocked" relative to each other such that each flexure from one cylinder would be coplanar (when not deflected) with one from the other cylinder. Hence, in essence, there would be three contiguous flexures connecting the two cylinders.

The advantages of this configuration are the following:

- The termination of the flexural elements would be brought as close as possible to the axis of rotation, thereby maximizing the rotational flexibility while maintaining lateral stiffness.
- Load paths through the device would be aligned such that all translational loads would be carried as tension or compression in the flexural elements (the stiffest and highest-load-bearing arrangement possible), while a torque applied about the axis of rotation would be reacted by simple bending (configuration of greatest compliance and least stress).

This work was done by Donald Moore and Robert Calvet of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1]. NPO-21154

Algorithm Computes Kinematics of a Rover on Rocky Terrain

This algorithm is efficient enough for use in a real-time simulation.

The Rover Analysis Modeling and Simulation (ROAMS) algorithm is to solve the kinematics of a wheeled mobile robot (rover) traversing on a rocky terrain. The rover is constructed using a "rocker-bogie-differential" type suspension and steering system as shown in the figure. By exploring the mechanical symmetry and the wheeled-terrain contact characteristics on a rough terrain profile, we developed a novel algorithm to carry out the rover's configuration, including the vehicle's wheels, steering and

suspension linkages, and the position and orientation of the chassis. Because of its efficient and reliable numerical results, the ROAMS algorithm is well suited for the real-time simulation test bed, e.g., a simulation software system, of the mobile robotic vehicles in the planetary surface exploration missions. Currently, it is used to support the development of simulation and operation tools for the Mars Exploration Rover (MER) in the Mars '03 mission.

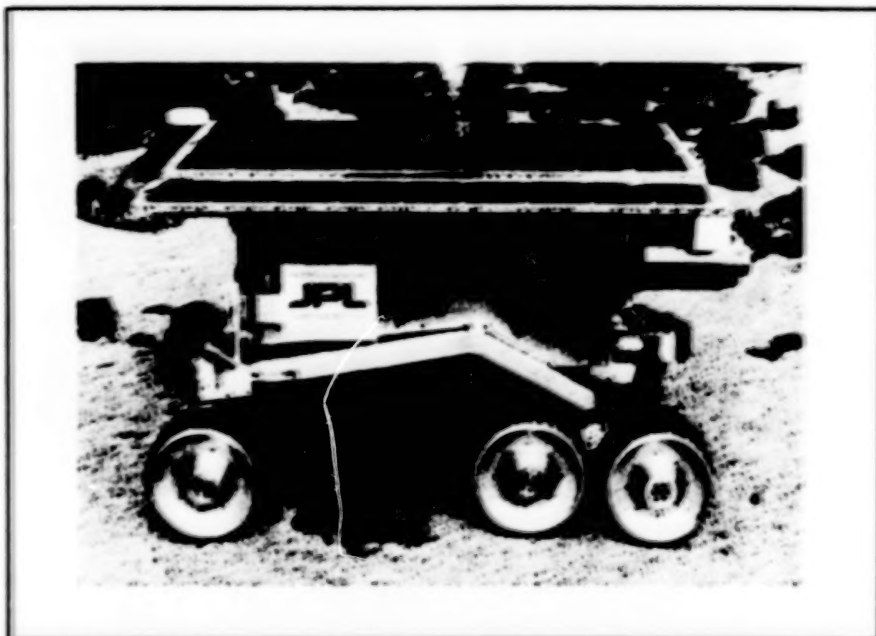
One of the most important properties of

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Pasadena, California

the algorithm is the robust computational result, which yields a fast prediction of the rover's position and orientation in an uncertain environment. The ROAMS algorithm treats the underlying mathematical model as an inverse kinematics problem, and carries out the solutions using the computational techniques for constrained optimization. In this framework, the objective functions comprise three conditions: (1) rover's internal differential mechanisms, (2) wheel-terrain contact, and (3) rover's

driving motion. The resultant nonlinear equations can be derived, and their solution can be computed by a straightforward application of numerical methods. However, the standard approaches to this nonlinear system of equations suffer from the instability and inefficiency in the numerical solutions due to the rough terrain profile, which is often modeled as a piecewise smooth digital elevation map (DEM). Moreover, the modeling of the physical limits of the linkages (e.g., the bumper-stops) can be problematic to the solution, as well as the case that all wheels may not be in contact with the ground at all times. All these modeling and numerical difficulties are resolved in the novel algorithm that achieves the real-time simulation of the rover traversal on a rocky terrain.

In this algorithm, we implemented a Newton-type iterative method that handles the non-smooth wheel-terrain contact equations using global searching and relaxation techniques. The solution also takes account for the bump-stopper devices, which have been modeled as the joint limits at the corresponding linkages, and maintains a fast convergent rate. Regular Newton-type iteration requires the smoothness of the equations to ensure a fast convergence. This prerequisite of a robust convergence is violated since the roughness of the terrain has been embedded in the contact equations. When the rocker or bogey linkages reach their limits, an abruptness of the iteration can induce unpredictable solution of the configuration. To overcome these numerical difficulties, we applied a weight factor to the residual of each contact equation. During the iterations, the weight factor for a given wheel can be made to approach zero to relax the contact condition. Whenever the wheel leaves the ground, its corresponding weight factor is set to zero for a total relaxation of this wheel-terrain contact. The re-scaling of the weight factors is coupled with the global search algorithm, which can



Rocky-7, a small robotic vehicle, is designed to traverse rocky terrain. The algorithm described in the text solves the inverse kinematic problem of the rover/terrain system during a computational simulation of such a traversal.

detect the joint limits (associated with each of the wheel-terrain contacts) for locking the joints, and can sample small perturbations around the contacting locations to determine the occurrence of a separation of the wheel and the ground.

The step-selection strategy used in the global search is a backtracking line search algorithm that monitors the progress of the iteration. For a smooth terrain profile, the iterative solution generated by the Newton method converges very rapidly to a local minimum of the nonlinear equations. However, the rate of convergence can be tremendously decreased when a non-smooth terrain profile appears. Special cares have to be taken to maintain robust and efficient solution in the case of non-smooth terrain profile. Although the problem in hand is ill-posed (i.e., it is well-known that the Newton method cannot treat non-smooth equations), we developed a heuristic solution to ease the computational difficulty in

the iterations. In practice, the wheel-terrain contact is treated as a non-penetrative type, which is not a realistic portrait of the nature of the wheel-terrain interaction. Therefore, a search direction to the wheel-terrain contact may not be in-line with the normal direction of the terrain (at the contact location), instead, it could be anywhere along the perimeter of the wheel. The heuristic solution leads to modeling the wheel-terrain contact equation as the distance constraint between the wheel center and the terrain profile. As shown in all the preliminary testing cases, the modification of contact equations yields a much-improved convergence in non-smooth terrain profiles, and allows the modified Newton iteration to overcome many local irregularities.

This work was done by Jeng Yen of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].
NPO-20997

Crowned Races for Crossed Roller Bearings

Scuffing would be reduced.

Crowned races have been proposed for crossed roller bearings. Crowning of the races is expected to reduce scuffing of the cylindrical rollers. Crowning of the races is expected to be especially beneficial in bearings made of polymers (instead of metals) to reduce weight.

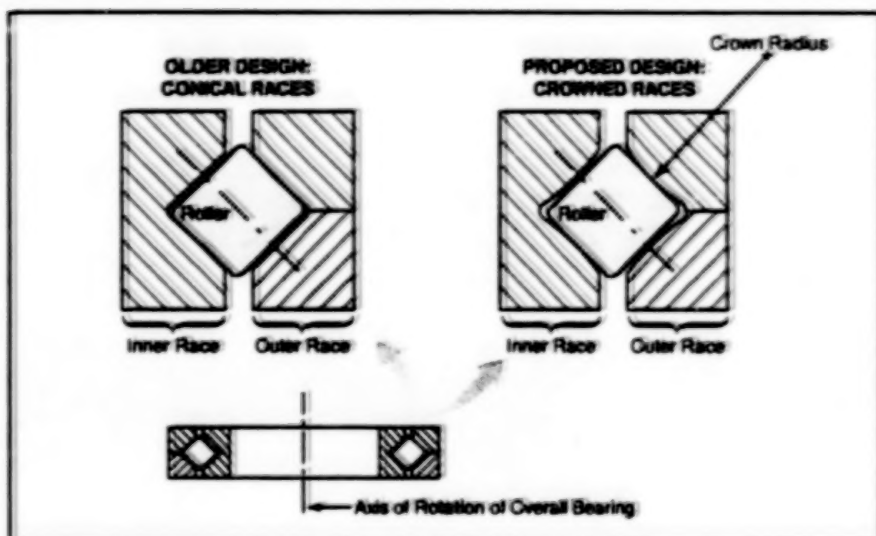
The crossed-roller bearing design is the roller equivalent of the x-type ball bearing

design. In a crossed-roller bearing, the races are conical surfaces at angles of 45° to the axis of rotation. The advantages and disadvantages of the ball and crossed-roller designs are complementary: In comparison with ball bearings, roller bearings can withstand greater loads. On the other hand, roller bearings are more susceptible to scuffing, which is caused by a kinematic mis-

match between tangential roller speeds at the inner and outer diameters of the races.

In a crossed-roller bearing with crowned races (see figure), the contact area, and thus the amount of scuffing, would be reduced (relative to that of conical races) to a value near that of ball bearings. The crown radius is a free design parameter that can be chosen, along with other parameters, in

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Crowned races, in contradistinction to conical races, would function with less scuffing in roller/race contact areas.

consideration of the bearing material(s) and the loads that must be borne in a given application.

One might ask why it would be preferable to crown the races instead of crowning the rollers. The reason is a practical one: Unlike in the case of steel bearing balls, it is difficult to fabricate polymeric bearing balls or polymeric crowned rollers with sufficient precision to ensure sharing of loads as needed for long bearing life. On the other hand, cylindrical crowned rollers of sufficient precision can be fabricated easily by centerless grinding in conventional machines.

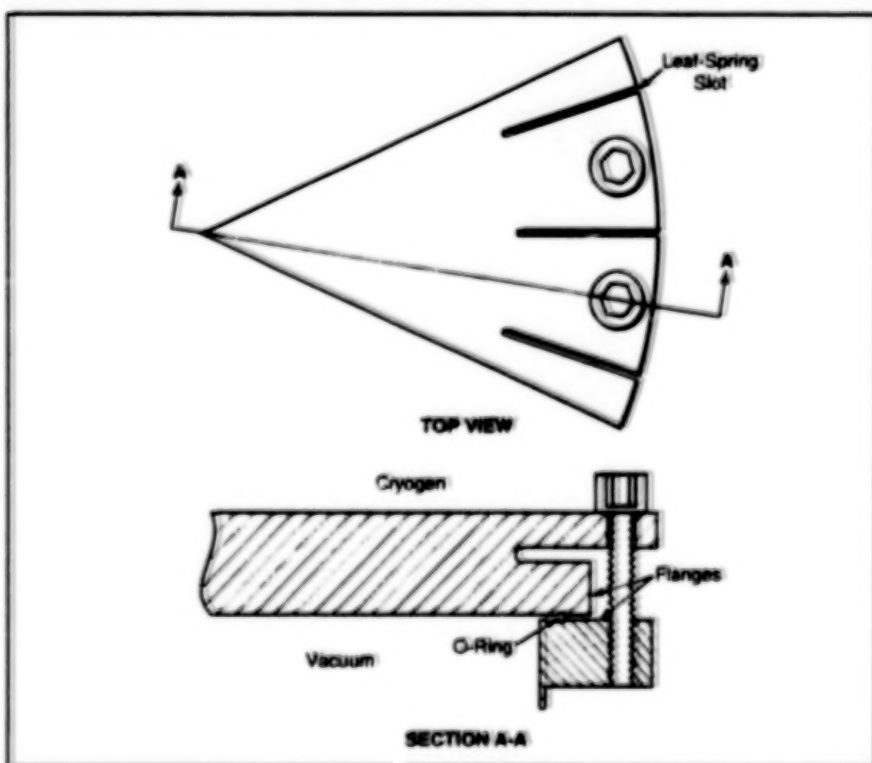
This work was done by Donald Bickler of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].

NPO-30203

Improved Flange Design for Cryogenic Vacuum O-Ring Seals

Spring-loaded joints could be made less bulky.

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The Outer Portion of One of the Flanges would be cut to form leaf springs, which would be used for spring loading of the O ring.

A compact spring-loading design has been proposed to increase the reliability of seals in the joints of vacuum cryogenic systems. Heretofore, such joints have

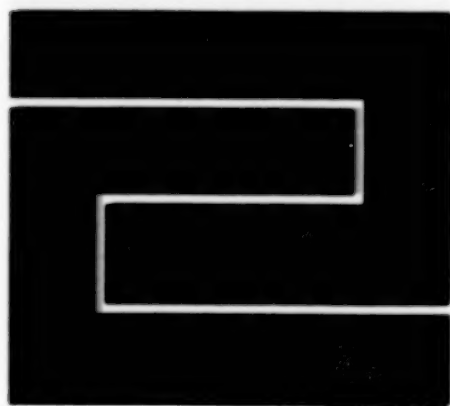
been, variously, compact or reliable, but not both, for the following reasons: In all such joints, sealing is effected by compression of soft metal (typically, indium or

alloys of indium) O rings between flanges. Over time, the soft O-ring metal flows, with consequent reduction of preload, sometimes leading to loss of seal. To ensure reliable seals, it is necessary to spring-load the flanges to maintain compression of the O rings. However, spring-loaded joints of traditional design are not compact.

The proposed compact spring-loading design is related to a prior noncompact design in which (1) one of the flanges of a joint is cut so that it acts somewhat like a leaf spring and (2) the bolt-circle diameter of the flange is made considerably greater than the major diameter of the O ring so that the flange can bend elastically and its deflection is spread out over the annulus between the O ring and the bolt circle. In the proposed design, leaf springs with a thickness less than that of the flange would be formed in the bolt-circle region by cutting a combination of meridional (radial) and annular slots in the flange, as shown in the figure. This design would afford the elasticity needed for spring loading, without need to make the bolt circle much larger than the O ring.

This work was done by Bob Bamford, Tatsuo Chui, and Warren Holmes of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].

NPO-21006



Fabrication Technology

Hardware, Techniques, and Processes

39 Etching Mirror Facets on SOI Optical Waveguides

Etching Mirror Facets on SOI Optical Waveguides

Surfaces of high optical quality could be mass-produced.

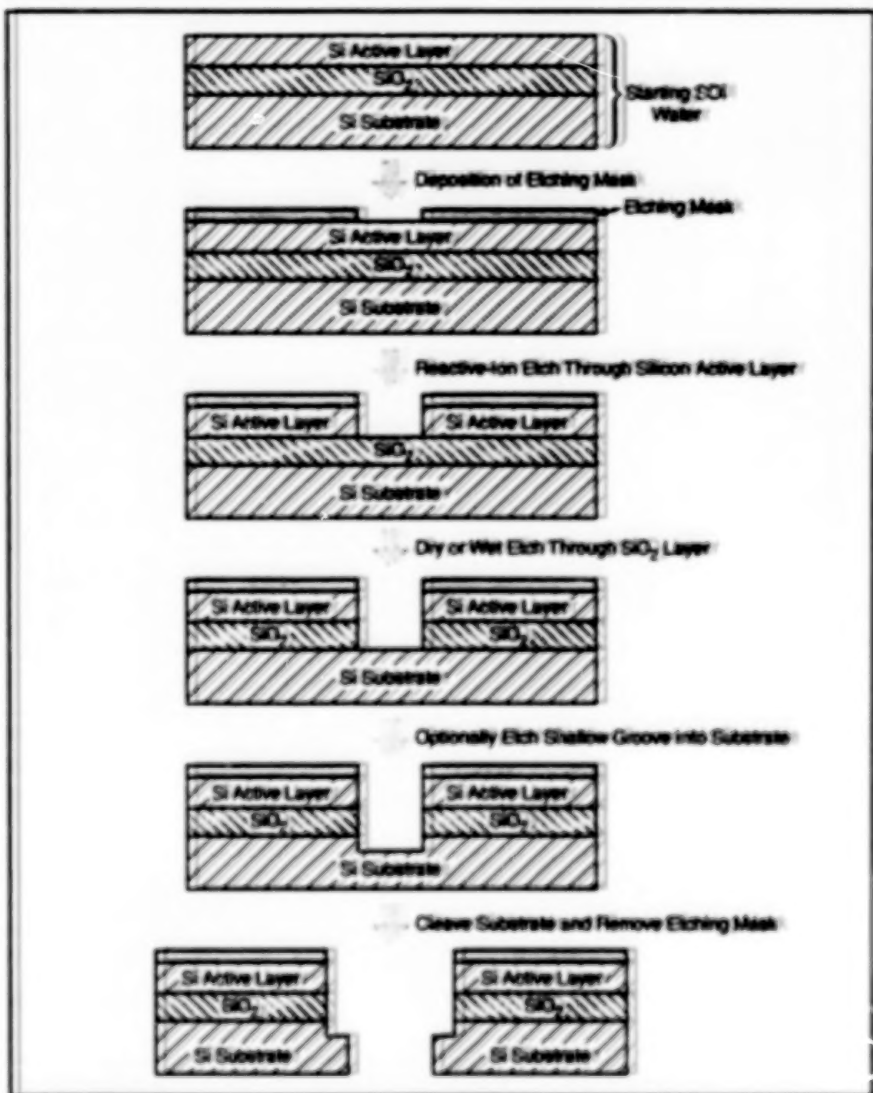
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Pasadena, California

A process that would include a combination of dry and wet chemical etching has been proposed for making facets for low-loss mirrors on silicon-on-insulator (SOI) optical waveguides. Heretofore, such facets have been made by a process that includes dicing and polishing. This process is time-consuming and thus not suitable for mass production; moreover, the optical quality of the facets is limited by the size of the powder grains used in polishing. (Although it is possible to make nearly optically perfect facets by cleaving, the yield achieved in practice is too low for mass production.)

The etching techniques in the proposed process are already used for mass production in the semiconductor and integrated-circuit industries, and are expected to yield facets with optical quality superior to that achievable by polishing. There are two versions of the proposed process. The main steps of the first version (see figure) are the following:

1. Deposit an etching mask on top of the silicon active layer.
2. Do a reactive-ion etch through the thickness of the silicon layer.
3. Do either a dry etch or a wet chemical etch through the thickness of the SiO_2 layer.
4. Optionally, etch a shallow groove into the silicon substrate.
5. Cleave the silicon substrate. A high yield can be obtained if one cleaves via an etched groove.
6. Remove the etching mask.

The main steps of the second version of the proposed process are nearly identical, except that one would turn the wafer upside-down and etch through the substrate first. The advantage of the second approach is that one would generate the facets by cleaving the silicon active layer; the quality of the facet would therefore be better than that achievable (by



Facets of High Optical Quality would be formed on the etched surfaces of the silicon active layer.

etching) in the first version.

This work was done by Chi Wu of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in *US TSP* [see page 1].

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

Intellectual Assets Office

JPL

Mail Stop 202-233

4800 Oak Grove Drive

Pasadena, CA 91109

(818) 354-2240

E-mail: ipgroup@jpl.nasa.gov

Refer to NPO-20757, volume and number of this NASA Tech Briefs issue, and the page number.



Mathematics and Information Sciences

Hardware, Techniques, and Processes

43 | Measuring Sea Height and Roughness With GPS Reflections

Books and Reports

43 | Time-Parallel Algorithms for Solving PDEs

Measuring Sea Height and Roughness With GPS Reflections

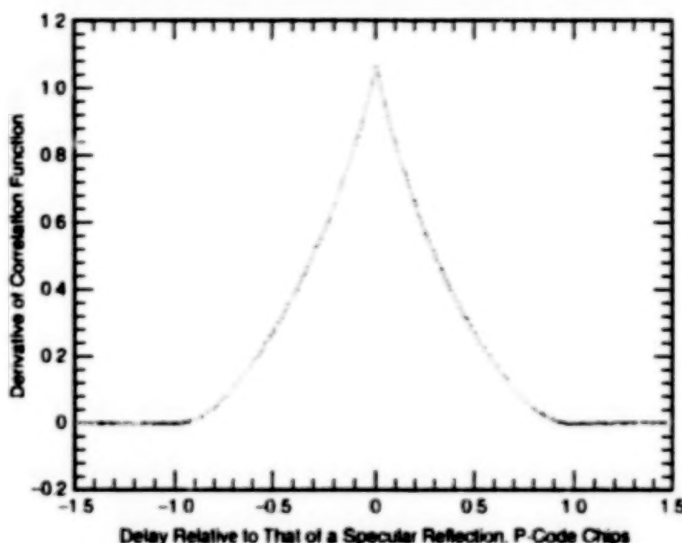
Dense and rapid coverage would enable new oceanographic applications.

NASA's Jet Propulsion Laboratory,
Pasadena, California

A proposed technique of bistatic radar altimetry would utilize information available in Global Positioning System (GPS) signals reflected from the ocean surface. The signals would be monitored by an airborne or spaceborne receiver and would be processed to determine the height, roughness, and possibly other properties of the surface. An important advantage of the proposed technique would be density and rapidity of coverage: Whereas a traditional nadir-looking radar altimeter gives the surface height at only one location below the altimeter, a receiver implementing the proposed technique could track about 10 GPS reflections simultaneously. Such dense coverage could translate to spatial and temporal resolutions greater than those previously achievable, and hence the ability to study ocean-topography features or processes beyond the reach of prior techniques. Potential applications could include monitoring of eddies and tides and tracking of fast barotropic waves.

The proposed technique is an extended version of the cross-correlation process used to extract time and position information from direct GPS signals. The extension to the reflected-signal case involves consideration of numerous factors, including the field of view and pointing direction of the receiving antenna, the angle of scattering of each affected GPS signal, the direction of the plane of incidence of the GPS signal relative to the velocity of the spacecraft or aircraft carrying the receiver, and the integration time of the receiver.

One function of particular importance for the mathematical foundation of the technique is the derivative of the correlation function (DCF) with respect to the model time delay. This function exhibits a sharp peak (see figure), the shape of which is affected in known ways by the wind speed and by surface-roughness statistics. Hence, in principle, one should be able to extract important sea-state parameters from the DCF. These parameters are, specifically, (1) the mean sea height (derived from knowledge of the location of



The Derivative of the Correlation Function with respect to delay time yields information on three sea-state parameters, as described in the text. The unit of delay time is one repetition period ("chip") of the GPS pseudonoise code — a period ≈ 0.1 second.

the DCF peak relative to the model delay), (2) the ocean-surface wind (derived from the height of the DCF peak), and (3) the significant wave height (derived from the width of the DCF).

The effects of the ionosphere, troposphere, and clock errors on the accuracy of the technique have been estimated, and an overall root-mean-square value of range accuracy has been predicted as a function of sea state and antenna gain. It has been found that when one averages many measurements collected from a possible constellation of receivers, the range error would be progressively reduced as a function of space and time, yielding predicted accuracies in estimated sea height with associated spatial and temporal resolutions. Preliminary calculations indicate that sea-height accuracies of a few cm on spatial scales of 100 km from measurements averaged over four days could be achievable.

The effect of wind speed and significant wave height on the received signal has been examined by computational simulation for realistic ranges of wind speeds and wave

heights. The bistatic geometry has been found to make the sea-height measurements less sensitive to wave heights than are the sea-height measurements of conventional nadir-viewing geometry. The electromagnetic bias of the scattered waveform has also been found to be reduced. The range accuracy versus receiving-antenna gain and scattering direction were also examined; it was found that at low elevation angles, both the scattering cross section and the coherence time are greater than those at nadir, resulting in a potential decrease of the range error for a fixed antenna gain. Finally, the possibility of tracking the phase of the GPS signal at small elevation angles and the resulting improvement in the range-measurement accuracy has also been examined theoretically.

This work was done by Cinzia Zuffada, George Hajj, and J. Brooks Thomas of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].
NPO-20943

Books and Reports

Time-Parallel Algorithms for Solving PDEs

These algorithms are particularly efficient for implementation on massively parallel MIMD computers.

A report presents additional details about a class of massively parallel algorithms for finite-difference numerical solution of time-dependent partial differential equations (PDEs). Some aspects of these algorithms were described in two previous articles in *NASA Tech Briefs*; namely, "Massively

Parallel Computation of Electromagnetic Fields" (NPO-19453), May 2002, page 51 and "Time-Parallel Solutions of Linear PDEs on a Supercomputer" (NPO-19385), December 1999, page 43. These algorithms are fully parallelized in time as well as in space: this is achieved via a set of

transformations based on eigenvalue/eigenvector decompositions of matrices obtained in discretizing the PDEs. Among other things, the report discusses efficient techniques for computing these decompositions for PDEs in which the spatial part involves Laplace's or Poisson's equation in two-dimensional Cartesian or polar coordinates. The time-parallel algorithms incorporate fully implicit solution methods that offer

numerical properties superior to those of explicit numerical-integration methods. Moreover, these algorithms feature a highly decoupled structure with minimal requirements for communication and synchronization among parallel processors. As a result, these algorithms are particularly efficient for implementation on massively parallel multiple-instruction, multiple-data (MIMD) parallel-processing systems.

This work was done by Amir Fijany, Jacob Barhen, and Nikzad Toomarian of Caltech for NASA's Jet Propulsion Laboratory. To obtain a copy of the report, "Time Parallel Algorithms for Solution of Time-Dependent Partial Differential Equations (PDEs)," see TSP's [page 1].
NPO-19433

END

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